



ON THE CHEMISTRY OF THE EARTH.

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In the following pages I have endeavored, at the request of Professor Henry, to give a brief summary of certain views in chemical geology which have been put forward by me in various scientific journals during the past twelve years, the germ of them having appeared in a communication to the *American Journal of Science* in January, 1858. In addition to the foot-notes, I have appended a list of my principal publications on the subject, where those who desire to follow up the various questions here suggested will find them treated more at length. The last three of these papers are in part reprinted in the present abstract. I take this occasion to say that the views here embodied will be developed in a work on the chemistry of the globe, the preparation of which is now well advanced.

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MONTREAL, January 6, 1870.

List of the principal papers, by Mr. T. Sterry Hunt, relating to Chemical Geology.

On the Chemistry of the Primeval Earth. *American Journal of Science*, January, 1858.

On the part which the Silicates of the Alkalies may play in the Metamorphism of Rocks. *Proc. Royal Society of London*, May 7, 1857, and *American Journal of Science*, March, 1858.

On the origin of Feldspars, and on some points of Chemical Lithology. *American Journal of Science*, May, 1858.

On the Theory of Igneous Rocks and Volcanoes. *Canadian Journal of Toronto*, March, 1858.

On some points in Chemical Geology. *Quarterly Journal of the Geological Society*, November, 1859.

Review of the last-named paper. *American Journal of Science*, July, 1860.

On Gypsums and Magnesian Rocks. *American Journal of Science*, September, November, 1859.

On the History of Lime and Magnesia Salts. *American Journal of Science*, July, 1866.

Contributions to Lithology. *American Journal of Science*, March, May, July, 1864.

Chemistry of Natural Waters. *American Journal of Science*, March, July, September, 1865.

Chemistry and Mineralogy of Metamorphic Rocks. *Dublin Quarterly Journal*, July, 1863.

Origin of some Magnesian and Aluminous Rocks. *American Journal of Science*, September, 1861.

La Chimie de la Terre. *Comptes-Rendus de l'Académie*, June 9, 1862.

The Earth's Climate in Paleozoic Times. *American Journal of Science*, 1863.

On some points in American Geology. *American Journal of Science*, May, 1861.

On the Chemical Geology of Mr. David Forbes. *Geological Magazine*, February, 1863.

On the Chemical Geology of Mr. David Forbes. *Chemical News*, February, 1868.

The Chemistry of the Primeval Earth. Lecture before the Royal Institution, May, 1867.

Volcanoes and Earthquakes. Lecture before the American Geographical Society, April, 1869.

On the Probable Seat of Volcanic Action. *Geological Magazine*, June, 1869.

CONTENTS OF SECTIONS.

1-3, classification of the sciences; 4, objects of chemical geology; 5, nebular hypothesis; 6, dissociation; 7, 8, the sun; 9, the cooling earth; 10-13, its solidification; 14, relations of solution to pressure; 15, on the earth's crust; 16, 17, probable composition and relation of earth's crust and atmosphere; 18, fixation of carbonic acid, its effect on climate; 19, chemical influence of vegetation as a reducing agent; origin of carbon and sulphurets; 20, origin of limestones, dolomites, and gypsums; 21, silicated waters; 22, relations of potash and soda; 23-26, disintegration of silicated rocks; 27, their division into two groups; 28, chemically-formed aluminous and non-aluminous silicated rocks; 29, changes in composition of sediments; 30, 31, metamorphism of rocks; 32, chemical alteration; 33, molecular alteration; 34, porosity of sediments, their condensation; 35, ultimate result of chemical metamorphism; 36, theory of volcanic action; 37, views of L. ferstein and Herschel; 38, the primitive crust; 39, internal heat; 40, 41, influence of pressure; 42, 43, types of igneous rocks; 44, origin of granites; 45, indigenous and exotic rocks; endogenous rocks or vein-stones; 46, filling of mineral veins; 47, source of metals, and theory of metalliferous deposits; 48, earthquakes; 49, volcanoes; 50, 51, their distribution; 52, causes of subsidence and accumulation of sediments; theory of mountains; 53, origin of lavas; 54, relations of sedimentary deposition to volcanic phenomena; ancient volcanoes; 55, modern volcanoes.

§ 1. In approaching the study of the chemistry of the earth, or what may be designated chemical geology, it becomes necessary to define the natural objects of that complex study to which is given the general name of geology, and also to consider its connection with the various sciences. To this end, some notions as to the order and the relation of these sciences may not be out of place. Following the classification established by Comte, we distinguish between the abstract sciences, which deal with laws, and the concrete sciences, which have to do with things. In their order the abstract sciences form an ascending series, according to the degree of complexity of their phenomena, "so that each science depends on the truths of all those which precede it, with the addition of peculiar truths of its own."—(J. S. Mill.) At the base of this series are thus placed—1st, *Mathematics*, with its successive divisions of number, geometry and mechanics; 2d, *Abstract Astronomy*, which considers, in addition to these, gravitation, taking cognizance of number, extension, equilibrium, and motion; 3d, *Physics*, comprehending the laws of weight, cohesion, sound, light, electricity, and magnetism; 4th, *Chemistry*, which treats of the relations to one another of the different forms of mineral matter, and their transformations under the physical agencies of light, heat, and electricity; 5th, *Biology*, or *Physiology*, to which belongs the study of the laws of organized growth and development; 6th, *Psychology*, which considers the laws of mental phenomena; and, 7th, *Sociology*, or the laws of human society.

§ 2. Parallel with these abstract sciences is a series of concrete or historical sciences, dealing not with laws and general principles, but with objects and facts. Of these concrete sciences the first is *Descriptive Astronomy*, which is the natural history of the planetary and stellar worlds, treating of their movements, dimensions, and cosmical relations. Coming, in the next place, to the history of our own planet, the study of the accidents of its surface and its interior gives rise to *Physical Geography* and to *Structural and Dynamical Geognosy*; while the bodies which it presents to us are naturally divided into two great classes, the inorganic or mineral kingdom, and the organic, including the vegetable and animal kingdom. The study of these two classes gives rise to two great branches of natural history, *Mineralogy* and *Organography*, the latter including *Botany* and *Zoology*. The concrete science of mineralogy has for its subject the natural history of all the forms of unorganized mat-

ter; that is to say, those substances which are exempt from biological laws, but come within the domain of physics and chemistry. Chemical change implies disorganization, and all so-called chemical species are inorganic, that is to say, unorganized, and belong to the mineral kingdom, whose natural history is thus physical and chemical, while that of the vegetable and animal kingdoms is biological.*

§ 3. It might, at first sight, seem foreign to our present subject to speak in this connection of the moral, social, and political history of mankind, dependent upon the laws of psychology and sociology. It is, however, to be remarked, that while in the abstract order each science is independent of that which follows it in the series, it is far different in the concrete sciences. This is seen in the familiar example of the dependence upon each other of the animal, vegetable, and mineral kingdoms, and it is evident that man puts in movement agencies which are constantly at work modifying alike physical geography and the relations of the mineral, vegetable, and animal world to such an extent that human history must not be disregarded in the study of the lower reigns of nature.

§ 4. From what has gone before it will be evident that under the common term of geology are generally confounded two distinct branches of study; the first or abstract division being that of the physical, chemical, and biological laws which have presided over the development of the globe, and the second or concrete division, the natural history of the earth as displayed in its physical structure, stratigraphy, mineralogy, paleontology. The name of geognosy, employed by some authors, may very appropriately be retained for the latter, while that of geology is restricted to the former division. It is proposed in the following pages to consider briefly some of the more important points in the chemical history of the globe; in doing which it will be necessary to notice also its astronomical and physical history, and the relations of organic life, in so far as they are concerned in the chemical history of the earth in its various stages of development. The scheme thus embraced is so great that in the limits of the present essay nothing more can be attempted than a sketch which shall embrace some of the most striking facts in the history of the forming globe considered as a condensing nebulous mass, in the chemistry of the air, sea, and earth in past ages, and in the relations of the central heat to the superficial portions of the earth, by which we shall endeavor to explain certain facts in dynamical geology, such as the great movements of the earth's crust and the phenomena of earthquakes and volcanoes.

§ 5. The nebular hypothesis, as it is called, which supposes that our solar system and all the worlds of space have come from the condensation of diffused vapors, has received strong confirmation from the discoveries made by the spectroscope. We now know that there exist in the heavens nebulae consisting of luminous gas; that is to say, vaporous matter shining by its own light, which we may, with great probability, regard as the primal matter out of which, as the elder Herschel suggested, suns and planets have been formed by a process of condensation. By the aid of the telescope and the spectroscope we find in the heavens, planets—bodies like our earth, shining only by reflected light; suns,—self-luminous, radiating light from solid matter; and, moreover, true nebulae, or masses of luminous vapor. These three forms represent three distinct phases in the condensation of the primeval matter, from which our own and other planetary systems have been formed.

* T. S. Hunt, on the Objects and Method of Mineralogy. *American Journal of Science*, [2,] xliii; 203.

This nebulous matter is conceived to be so intensely heated as to be in the state of true gas or vapor, and, for this reason, feebly luminous when compared with the sun. It would here be out of place to discuss the detailed results of spectroscopic investigation, or the beautiful and ingenious methods by which modern science has shown the existence in the sun, and in many other luminous bodies in space, of the same chemical elements that are met with in our earth.

§ 6. Calculations based on the amount of light and heat radiated from the sun show that the temperature which reigns at its surface is so great that we can hardly form an adequate idea of it. Of the chemical relations of such intensely heated matter modern chemistry has made known to us some curious facts, which help to throw light on the constitution and luminosity of the sun. Heat, under ordinary conditions, is favorable to chemical combination, but a higher temperature reverses all affinities. Thus, the so-called noble metals, gold, silver, mercury, &c., unite with oxygen and other elements; but these compounds are decomposed by heat, and the pure metals are regenerated. A similar reaction was many years since shown by Mr. Grove with regard to water, whose elements—oxygen and hydrogen—when mingled and kindled by flame, or by the electric spark, unite to form water, which, however, at a much higher temperature, is again resolved into its component gases. Hence, if we had these two gases existing in admixture at a very high temperature, cold would actually effect their combination precisely as heat would do if the mixed gases were at the ordinary temperature, and literally it would be found that "frost performs the effect of fire." The recent researches of Henry Sainte-Claire Deville and others go far to show that this breaking-up of compounds, or dissociation of elements by intense heat is a principle of universal application; so that we may suppose that all the elements which make up the sun or our planet would, when so intensely heated as to be in that gaseous condition which all matter is capable of assuming, remain uncombined, that is to say, would exist together in the condition of what we call chemical elements, whose further dissociation in stellar or nebulous masses may even give us evidence of matter still more elemental than that revealed by the experiments of the laboratory, where we can only conjecture the compound nature of many of the so-called elementary substances.

§ 7. The sun, then, is to be conceived of as an immense mass of intensely heated gaseous and dissociated matter, so condensed, however, that notwithstanding its excessive temperature, it has a specific gravity not much below that of water; probably offering a condition analogous to that which Cagniard de la Tour observed for volatile bodies when submitted to great pressure at temperatures much above their boiling point. The radiation of heat going on from the surface of such an intensely heated mass of uncombined gases will produce a superficial cooling, which will permit the combination of certain elements, and the production of solid or liquid particles; these, suspended in the still dissociated vapors, become intensely luminous, and form the solar photosphere. The condensed particles, carried down into the intensely heated mass, again meet with a heat of dissociation, so that the process of combination at the surface is incessantly renewed, while the heat of the sun may be supposed to be maintained by the slow condensation of its mass; a diminution by $\frac{1}{1000}$ th of its present diameter being sufficient, according to Helmholtz, to maintain the present supply of heat for twenty-one thousand years.

§ 8. This hypothesis of the nature of the sun and of the luminous process going on at its surface is the one lately put forward by Faye,

and, although it has met with opposition, appears to be that which accords best with our present knowledge of the chemical and physical conditions of matter, such as we must suppose it to exist in the condensing gaseous mass which, according to the nebular hypothesis, should form the center of our solar system. Taking this, as we have already done, for granted, it matters little whether we imagine the different planets to have been successively detached as rings during the rotation of the primal mass, as is generally conceived, or whether we admit with Charnac a process of aggregation or concretion operating within the primal nebular mass, resulting in the production of sun and planets. In either case we come to the conclusion that our earth must at one time have been in an intensely heated gaseous condition such as the sun now presents, self-luminous, and with a process of condensation going on at first at the surface only, until by cooling it must have reached the point where the gaseous center was exchanged for one of combined and liquefied matter.

§9. Here commences the chemistry of the earth, to the discussion of which the foregoing considerations have been only preliminary. So long as the gaseous condition of the earth lasted, we may suppose the whole mass to have been homogeneous; but when the temperature became so reduced that the existence of chemical compounds at the center became possible, those which were most stable at the elevated temperature then prevailing, would be first formed. Thus, for example, while compounds of oxygen with mercury, or even with hydrogen, could not exist, oxides of silicon, aluminium, calcium, magnesium, and iron might be formed and condensed in a liquid form at the center of the globe. By progressive cooling, still other elements would be removed from the gaseous mass, which would form the atmosphere of the non-gaseous nucleus. We may suppose an arrangement of the condensed matters at the center according to their respective specific gravities, and thus the fact that the density of the earth as a whole is about twice the mean density of the matters which form its solid surface may be explained. Metallic or metalloidal compounds of elements, grouped differently from any compounds known to us, and far more dense, may exist in the center of the earth. The condensing effect of pressure as we approach the center of the globe has, however, been regarded by some as far more than sufficient to account for the considerable mean density of the planet, and, according to Dr. Young, would be sufficient to reduce a mass of granite, transported to the earth's center, to one-eighth of the bulk which it occupied at the surface, which would give to the earth a mean density equal to twelve or thirteen times that of water. This consideration has led a recent writer to conclude, with Herbert Spencer, that our earth and the other planets may be only shells of varying thickness, inclosing a central cavity filled with vaporous matter, by which hypothesis may be explained their apparently feeble density. It is, however, a matter of indifference, so far as our argument is concerned, whether the process of condensation commenced around such a central cavity, or at the center of the globe itself.

§10. The processes of combination and cooling having gone on until those elements which are not volatile in the heat of our ordinary furnaces were condensed into a liquid form, we may here inquire what would be the result, upon the mass, of a further reduction of temperature. It is generally assumed that in the cooling of a liquid globe of mineral matter, congelation would commence at the surface, as in the case of water; but water offers an exception to most other liquids, in-

asmuch as it is denser in the liquid than in the solid form. Hence, ice floats on water, and freezing water becomes covered with a layer of ice, which protects the liquid below. Some metals and alloys resemble water in this respect. With regard to most other substances, and notably the various minerals and earthy compounds like those which may be supposed to have made up the mass of the molten globe, the case is entirely different. The numerous and detailed experiments of Charles Deville, and those of Delesse, besides the earlier ones of Bischof, unite in showing that the density of fused rocks is much less than that of the crystalline products resulting from their slow cooling, these being, according to Deville, from one-seventh to one-sixteenth heavier than the fused mass, so that if formed at its surface they would, in obedience to the laws of gravity, tend to sink as soon as formed.

§ 11. The stony materials of the earth's crust then, unlike ice and certain metals, expand in melting and contract in passing into the solid state. The melting of ice is a process of condensation, and hence pressure favors its liquefaction, causing it to melt at a lower temperature than it would otherwise do; but for bodies with which melting is a process of expansion, pressure produces an opposite effect, namely, that of augmenting the fusing point. These conclusions of James Thompson and William Thompson have been experimentally verified by Bunsen, Fairbairn, and Hopkins. It results from this physical law that the effect of pressure upon materials like molten rocks would be such that solidification at a depth from the surface would take place at a temperature much higher than that required for their solidification at the surface. Hence, in opposition to the notion of a congealed layer, like a sheet of ice, resting upon the surface of a molten globe, Hopkins, and with him Scrope, supposes solidification to have commenced at the center of the liquid mass and to have advanced toward the circumference. Mr. Hopkins concludes that the pressure existing at great depths must have induced congelation of the molten mass at temperatures at which, under a less pressure, it would have remained liquid. Before the last portions became solidified, there was produced, it is conceived by Mr. Hopkins, a condition of imperfect liquidity, preventing the sinking of the cooled and heavier particles, and giving rise to a superficial crust, from which solidification would proceed downward. There would thus be inclosed between the inner and outer solid parts, a portion of uncongealed matter, which, according to him, may be supposed still to retain its liquid condition, and to be the seat of volcanic action, whether existing in isolated reservoirs or subterranean lakes, or whether, as suggested by Scrope, forming a continuous sheet surrounding the solid nucleus.

§ 12. This view of the constitution of the globe, or one analogous to it, has found favor with many theorists. Professor N. S. Shaler, of Harvard, who, in a recent essay on the formation of mountain chains, in the proceedings of the Boston Society of Natural History, has adopted it, concisely states it as follows: "The earth consists of an immense solid nucleus, a hardened outer crust, and an intermediate region of comparatively slight depth, in an imperfect state of igneous fusion." In this connection it is curious to remark that, as lately pointed out by Mr. J. Clifton Ward, Halley was led, from the study of terrestrial magnetism, to a similar hypothesis. He supposed the existence of two magnetic poles situated in the earth's outer crust, and two others in an interior mass, separated from the solid envelope by a fluid medium, and revolving, by a very small degree, slower than the

outer crust.* The same conclusion was subsequently adopted by Hansteen.

§ 13. Apart from these considerations, however, many of the best modern physicists and geologists have found numerous reasons for rejecting the popular notion which regards our globe as a liquid molten mass covered by a layer of twenty or thirty miles of solidified rock. The deductions of Hopkins from the phenomena of precession and nutation, those of Pratt from the crushing force of immense mountain masses like those of the Himalaya, and those of Sir William Thompson from the tides, showing the great rigidity of the earth, all unite to prove that the earth, if not solid to the center, must have a firm and solid crust several hundred miles in thickness. Under these conditions, if there still exist a liquid center, it must, so far as superficial phenomena are concerned, be as inert as if it were not. We are thus prepared to accept the conclusions to which the line of argument in § 11 leads us, and admit that our globe solidified from the center.

§ 14. It is, then, with the superficial portions of the earth, alone, that we have to do from the moment of its solidification; and as in the subsequent pages of our history air and water must play an important part, it becomes necessary, before going further, to consider briefly the nature of the process of aqueous solution and its relations to pressure. Solution may, for our present purpose, be defined as a chemical union between two or more bodies, of which one is liquid, resulting in a liquid product, and accompanied by a change of volume.† In ordinary cases, as in that of most bodies dissolving in water, this change is in the direction of condensation, and hence, as might be expected, pressure exerts an influence similar to that in the liquefaction of certain bodies by fusion, explained in § 11. Pressure facilitates the liquefaction of ice, which is attended by condensation, and acts in like manner in the case of solution, so that the solubility of salts in water, as shown by the experiments of Sorby, is increased by pressure. We can scarcely doubt that these phenomena of fusion and solution come under one general physical law, and that for all those bodies which contract in dissolving, (to which there are but few exceptions,) their solubility in water must be augmented by and in proportion to the pressure. As expressed by Mr. Sorby, mechanical is thus converted into chemical force.‡

§ 15. Reverting now to the solidified globe, in whose superficial portions and in the surrounding gases and vapors were present all the chemical elements with which we have to do, it is necessary to consider briefly its physical and its chemical condition at this early period.

The formation of a crust at the surface of the viscid layer which still enveloped the solidified mass of the globe, as conceived by Hopkins, is readily admissible; but that this process commenced when the remaining envelope of liquid matter was yet so deep that the refrigeration up to the present time has not been sufficient for its entire solidification is not probable. Such a crust on the cooling superficial layer would, from the contraction consequent on the further refrigeration of the liquid stratum beneath, become more or less depressed, corrugated, and

* The elevated temperature of the interior of the globe would probably offer no obstacle to the development of magnetism. In a recent experiment of M. Trève, communicated by M. Faye to the French Academy of Sciences, it was found that molten cast iron when poured into a mold, surrounded by a helix which was traversed by an electric current, became a strong magnet when liquid at a temperature of $1,300^{\circ}$ C., and retained its magnetism while cooling. (*Comptes-Rendus de l'Académie des Sciences*, February, 1869.)

† T. S. Hunt, *Thoughts on Solution*, American Journal of Science, [2,] xix, 100.

‡ Bakerian Lecture for 1863, L. E. and D. Philosophical Magazine, February, 1864.

broken up, thus causing the extravasation of the yet unsolidified portion, which would contribute to the vast amount of mineral matter brought within the chemical influences of the surrounding atmosphere. Further contraction from cooling would render this material more or less porous and permeable, preparing it for that process of combined mechanical and chemical disintegration which would result from the action of the acid liquids afterwards to be precipitated from the atmosphere.

§ 16. We have next to consider the chemical constitution of this irregular surfaced and broken-up crust of anhydrous and primitive igneous rock, which is now everywhere buried beneath the products of its disintegration. It is evident that, with the exception of those which were still in a gaseous form, it must have contained all the elements which now make up the known rocks of the earth's crust. If we conceive these, together with the air, the ocean, and its dissolved salts, now to react upon each other under the influence of an intense heat, it will enable us to form some notion of the chemical relations of the elements of the globe at the time when they were cooling down from that condition of igneous vapor which we suppose to have been that of our planet at an early stage in its history. To the chemist it is evident that from such a process applied to our globe would result the oxidation of all carbonaceous matter, the conversion of all carbonates, chlorides, and sulphates, into silicates, and the separation of the carbon, chlorine and sulphur in the form of acid gases, which, with nitrogen, watery vapor, and an excess of oxygen, would form an exceedingly dense atmosphere. The resulting fused mass would contain all the bases as silicates, and would probably nearly resemble in composition certain furnace-slugs or basic volcanic glasses. Such we may conceive to have been the nature of the primitive igneous rock, and such the composition of the primeval atmosphere, which must have been one of very great density. Under the pressure of a high barometric column condensation would take place at a temperature much above the present boiling point of water, and the lower levels of the half-cooled crust would be drenched with a highly heated solution of hydrochloric acid, whose decomposing action would be powerfully aided by the temperature. The formation of chlorides of the various bases, and the separation of silica, would go on until the affinities of the acid were satisfied, while there would result a sea-water holding in the solution, besides the chlorides of sodium, calcium, and magnesium, salts of aluminum and other metallic bases. At a later period the gradual combination of oxygen with sulphurous acid would eliminate this from the atmosphere in the form of sulphuric acid. The atmosphere being thus deprived of its volatile compounds of chlorine and sulphur, would approach to that of our own time, but differ in its much greater amount of carbonic acid. It will be remarked that from the affinities which would come into play in the conditions above supposed, all the elements, with the exception of the noble metals, nitrogen, chlorine, the related haloids, and the hydrogen combined with these, would be united with oxygen. The volatility of gold, silver, and platinum, would keep them still in a gaseous condition at temperatures where silicon, and with it the baser metals, were precipitated in the form of oxides.

§ 17. The process just described ceased with the separation from the air of the compounds of sulphur and chlorine, and then commenced the second stage in the action of the atmosphere on the earth's crust, by which, under the influence of carbonic acid and moisture, its complex aluminous silicates are converted into a hydrated silicate of alumina or clay; while the separated lime, magnesia, and alkalies, being changed into bicarbonates, are conveyed to the sea in a state of solution.

The first effect of these dissolved carbonates would be to precipitate the dissolved alumina and the heavy metals, after which came the decomposition of the chloride of calcium and the formation of carbonate of lime and chloride of sodium. This action of carbonic acid is still going on at the earth's surface, slowly breaking down and destroying the hardest rocks, and, aided by mechanical processes, transforming them into clays; although the action, from the comparative rarity of carbonic acid in the atmosphere, is now less energetic than in earlier times, when the abundance of this gas, and a higher temperature, favored the chemical decomposition of the rocks. But now, as then, every clod of clay formed from the decay of a crystalline rock corresponded to an equivalent of carbonic acid abstracted from the atmosphere, and to equivalents of carbonate of lime and common salt formed from the chloride of calcium of the sea-water.

It is very instructive, in this connection, to compare the composition of the waters of the modern ocean with that of the sea in ancient times, whose composition we learn from the fossil sea-waters which are still to be found in certain regions, imprisoned in the pores of the older stratified rocks, and are the source of many of our saline mineral waters*. These are vastly richer in salts of lime and magnesia than those of the present sea, from which have been separated, by chemical processes, all the carbonate of lime of our limestones, with the exception of that derived from the sub-aërial decay of calcareous and magnesian silicates belonging to the primitive crust.

§ 18. The gradual removal, in the form of carbonate of lime, of the carbonic acid from the primeval atmosphere, has been connected with great changes in the organic life of the globe. The air was doubtless at first unfit for the respiration of warm-blooded animals, and we find the higher forms of life coming gradually into existence as we approach the present period of a purer air. Calculations based upon the probable amount of limestone in the earth's crust, lead us to conclude that the amount of carbon thus removed in the form of carbonic acid has been so enormous, that we must suppose the earlier forms of air-breathing animals to have been peculiarly adapted to live in an atmosphere which would probably be too impure to support modern reptilian life.

Growing plants under the stimulus of light possess, as is well known, the power to absorb carbonic acid, appropriating the carbon and liberating oxygen. The importance of this agency in purifying the primitive atmosphere was long since pointed out by Brongniart, and our great stores of fossil fuel have been derived from the decomposition, by the ancient vegetation, of the excess of carbonic acid of the early atmosphere, which, through this agency, was exchanged for oxygen gas. In this connection the vegetation of former periods presents the curious phenomenon of plants allied to those now growing beneath the tropics flourishing within the polar circles. Many ingenious hypotheses have been proposed to account for the warmer climate of earlier times, but are at best unsatisfactory, and it would appear that the true solution of the problem may be found in the constitution of the early atmosphere, when considered in the light of Dr. Tyndal's beautiful researches on radiant heat. He has found that the presence of a few hundredths of carbonic acid gas in the atmosphere, while offering almost no obstacle to the passage of the solar rays, would suffice to prevent almost entirely the loss by radiation of obscure heat.

The aqueous vapor which our atmosphere contains exerts a powerful

* T. S. Hunt. Contributions to the Chemistry of Natural Waters, American Journal of Science, [2.] XXXIX, 184.

influence of the same kind, allowing the sun's rays to reach the earth, but preventing to a great extent the loss by radiation of the heat thus communicated. When, however, the supply of heat from the sun is interrupted at night, the radiation which goes on into space causes the precipitation of a great part of the watery vapor from the air, and the earth, being thus deprived of its protecting shield, becomes more and more rapidly cooled. If now we could suppose the atmosphere to be mingled with some permanent gas which should possess an absorptive power like that of aqueous vapor, this cooling process would be in a great measure arrested, and an effect would be produced similar to that of a screen of glass, which keeps up the temperature beneath it, both directly by preventing the escape of radiant heat, and indirectly by hindering the condensation of the aqueous vapor in the air confined beneath. Such a gas is carbonic acid, and the large amount of it which existed in the atmosphere during former geological periods must have aided greatly to maintain the elevated temperatures which then existed at the earth's surface. Without doubt the greater extent of sea and the absence or rarity of high mountains contributed much to the mild climate of former geologic ages; but to these must be added the influence of the whole of the carbon since condensed in the forms of carbonate of lime and coal, which then existed as a transparent and permanent gas mingled with the atmosphere surrounding the earth, and protecting it like a dome of glass. To this effect of carbonic acid it is possible that other gases may have contributed. The ozone which is mingled with the oxygen set free from growing plants, and the marsh-gas which is now evolved from decomposing vegetation, may, by their absorptive powers, which are far greater than that of carbonic acid, have contributed greatly to maintain a high temperature at the earth's surface in early times.*

§ 19. The part which vegetation has played in the chemical history of the globe has not been limited to the purification of the atmosphere. It seems to have been the great agent through which solar force has effected a partial deoxidation of the thoroughly burned or oxidized materials of the primitive world. By means of growing plants carbonic acid and water are reduced, giving rise to the various forms of carbon and to hydrocarbonaceous bodies, and these have been the agents by which the sulphates of the metals have been deoxidized, and sulphur, native metals, and metallic sulphides produced. It is moreover by the reducing action of decaying organic matters that the peroxide of iron is partially reduced and removed in a soluble form from sediments, to be afterwards deposited in the form of iron ore. The evidences of this reducing and dissolving action of organic matter are met with not only in the fire-clays and iron-stones of the carboniferous system, and among secondary, tertiary, and modern deposits, but on a grand scale in the Laurentian system, where great thicknesses of sediments are found almost destitute of iron, while beds of iron ore more extensive than at any subsequent periods are evidences of the abundance of organic matters at that early time. If these are not more frequently preserved in the form of anthracite and graphite, it is because the amount of peroxide of iron diffused through the sediments of the period furnished the oxygen necessary for the oxidation of the carbon. Inasmuch as the ores of these old rocks, in their present forms of hematite and magnetite, are very insoluble, and represent so much iron withdrawn from the terrestrial circulation, it is evident that the proportion of this element, existing in a dif-

* T. S. Hunt, On the Earth's Climate, etc., American Journal of Science, [2,] xxxvi, 396, 1863.

tured and oxidized state in recent sediments, must be less in those of more remote times.*

To the chemist the presence of graphite, or of a metallic sulphide in a rock, affords clear evidences of the intervention of organic life; and these indirect evidences are met with not only in the oldest known stratified rocks, those of the Laurentian system, but in the eruptive diorites, which rise from beneath them, and are pyritiferous. The presence of graphite, native iron, and sulphurets in most *aërolites*, not to mention the hydrocarbonaceous matters which they sometimes contain, tells us in unmistakable language that these bodies come from a region where vegetable life has performed a part not unlike that which still plays on our globe, and even lead us to hope for the discovery in them of organic forms which may give us some notion of life in other worlds than our own.

§20. Animal life has played in the chemical history of our planet a part much less important than vegetation, since it is entirely dependent for support upon the products elaborated for it by plants, and by chemical forces. Thus, although many limestones are made up chiefly, and even wholly of the calcareous remains of marine animals, these did no more than appropriate from the water the carbonate of lime generated by the chemical actions explained in §17. If the waters of the present ocean do not deposit carbonate of lime, it is simply because the amount of it now generated by the slow decomposition of the solid rocks is not more than is required for the living organisms which it contains. Let these become extinct and the supply of carbonate of lime, which would still continue, would soon cause deposits of precipitated carbonate of lime. Such a condition of things existing in past ages, in limited basins, has given rise to sediments of this kind, which constitute some of the finest statuary marbles.

The waters charged with the products of the sub-aërial decay of rocks, convey to the sea, as we have seen, bicarbonates of alkalis, lime, and magnesia; but from the reaction of these on the chloride and sulphate of calcium in the ocean waters carbonate of lime alone separates, since bicarbonate of magnesia decomposes chloride of calcium with formation of magnesian chloride. When, however, in a closed sea-basin all of the chloride of calcium is decomposed, the chloride of magnesium is attacked by the alkaline carbonates, and the resulting carbonate of magnesia is separated, mixed with the carbonate of lime which had accompanied these.

When into a similar closed basin, or an evaporating salt lake in a dry region, holding sulphate of magnesia, there is conveyed a water charged with bicarbonate of lime, there results a double decomposition, giving rise to sulphate of lime and bicarbonate of magnesia. The latter, being the more soluble salt, remains dissolved, while the sulphate of lime crystallizes out in the form of gypsum, but at a later period is deposited as a hydrated carbonate of magnesia, generally mixed with carbonate of lime. To effect this reaction it is necessary that there should be present such an excess of carbonic acid as to keep the magnesia in the condition of bicarbonate until the gypsum has crystallized out, inasmuch as dissolved sulphate of lime is readily decomposed by carbonate of magnesia. This condition can only be attained by especial precautions in the atmosphere of our period; but by operating in an atmosphere more highly charged with carbonic acid, the production of gypsum and magnesian carbonate by this reaction is readily effected. We may hence conclude that it was the more highly carbonated atmosphere of early periods which

* *Geology of Canada*, 1863, p. 573.

avored the accumulation of the great beds of gypsum and magnesian limestones which generally accompany the salt deposits of past geological periods. The hydrated magnesian carbonate, whether the concomitant of gypsum, as in this case, or of chloride of sodium, as in the former reaction, unites chemically with the associated carbonate of lime, and gives rise to dolomite or magnesian limestone.*

§ 21. The action of carbonated alkaline waters on the salts of the sea under ordinary conditions thus gives rise to carbonate of lime, and it is only under peculiar circumstances that magnesian carbonate is separated. The case is, however, changed with silicated alkaline waters coming from deep-seated silicated rocks, which undergo a decomposition without the intervention of the atmospheric air, and hold dissolved silicates of alkalies and of lime. These reacting on the magnesian salts dissolved in sea-water give rise to magnesian silicates, which are very insoluble. Hence we frequently find deposits of magnesian silicates in sediments, while silicates of lime are comparatively rare. In the solubility of bicarbonate of magnesia and the insolubility of the corresponding lime salt, and in the insolubility of magnesian silicate and the solubility of silicate of lime, we find a simple explanation of the geological relation of calcareous and magnesian silicates and carbonates.†

§ 22. The relations of the alkalies, potash and soda, require some consideration in this connection. The silico-aluminous compounds of potash possess a much greater degree of stability than those of soda. This is exemplified in the case of rocks which contain, side by side, orthoclase and albite, or oligoclase, when it is often found that the soda-feldspar has undergone decomposition from a loss of a portion of its alkali and partial disintegration, while the orthoclase or potash-feldspar remains unchanged. It is well known that waters holding large portions of potash salts in solution, exchange the potash for soda when filtered through a stratum of earth in which the amount of potash is, nevertheless, as great or greater than the soda; and we find that in natural spring-waters, which often contain considerable amounts of alkaline carbonates, the proportion of potash to the soda is as small as in the ocean. Surface-waters bearing the unfiltered wash of the land carry considerable portions of potash to the sea, but it is constantly removed, partly, at least, by the agency of fucoids, which, as Forchhammer has shown, like land-plants, take up large amounts of potash, and subsequently, by their decay in contact with the argillaceous mud, restore the alkali in an insoluble form to the earth. The formation of glauconite, a peculiar silicate rich in potash, which has been going on in the bottom of the sea from a very early period to the present time, has also been constantly withdrawing the potash from the ocean, so that soda is still the predominant base in its waters.

§ 23. The changes of silicated rocks under the influence of water, carbonic acid, and the products of decaying organic matter, present several points of interest. The chemical decomposition of feldspars consists in the removal of their protoxide bases, alkalies, and lime, together with a portion of silica, leaving as a final result a hydrous silicate of alumina or clay. This change is favored by mechanical division, and Daubrée has shown that by the prolonged attrition of the particles of granite under water, the softer and cleavable feldspar is, in great part, reduced to an impalpable powder, while the uncleavable quartz forms rounded grains of sand, the water at the same time dissolving from the feldspar a

* T. S. Hunt, On the Salts of Lime and Magnesia. American Journal of Science, [2,] xlii, 49.

† T. S. Hunt, American Journal of Science, [2,] xl, 49.

certain portion of alkali and silica. The soda-feldspars, being more easily decomposed and disintegrated by atmospheric influences, are broken up by mechanical agencies more readily than the potash-feldspar. The same is true of silicates like hornblende and pyroxene, which are less hard than the feldspars. From the mechanical and chemical disintegration of ordinary crystalline rocks, which consist chiefly of these various minerals, together with quartz, there will result a coarse sandy sediment, in which quartz with more or less orthoclase will prevail, while the finer mud will contain only the more minutely divided particles of these, together with partially decomposed soda-feldspar, clay, and the comminuted hornblende and pyroxene.

§ 24. This process is evidently one which must go on in the wearing away of rocks by aqueous agency, and explains the fact that while quartz, or an excess of combined silica, is, for the most part, wanting in rocks which contain a large portion of alumina, it is generally abundant in those rocks in which potash-feldspar predominates. The coarser and more silicious sediments are readily permeable to infiltrating waters, which gradually remove from them the soda, lime, and magnesia which they still contain, and, if organic matters intervene, the oxide of iron, leaving at last little more than silica, alumina, and potash, the elements of granite, trachyte, gneiss, and mica-schist. On the other hand, the finer sediments, whose origin, simultaneous with the coarser, we have just explained, resisting the penetration of waters, will retain all their soda, lime, magnesia, and iron-oxide, and containing an excess of alumina, with a small amount of silica, may, by their metamorphism, give rise to basic lime and soda-feldspars, and to pyroxene and hornblende—the elements of diorites and dolerites.

§ 25. The disintegration of alkaliferous rocks, however, frequently takes place under such conditions as to be more mechanical than chemical, and it may often happen that sediments still retaining a considerable amount of combined soda become mingled with carbonates of lime and magnesia. The reaction which then goes on between the liberated alkaline silicate and these earthy carbonates gradually effects the conversion of these into silicates, while the alkali is eliminated in the form of soluble carbonate of soda, giving rise to alkaline mineral waters, which, as I have shown, are abundantly generated in sediments where feldspathic matters and earthy carbonates are intermingled. It is only from rocks destitute of these carbonates that silicated alkaline waters can issue.

§ 26. A decomposition more exclusively chemical is observed particularly among the crystalline schists of tropical and semi-tropical regions, where a process of disintegration often destroys the cohesion of the rocks to a considerable depth. This change, which has been but imperfectly studied, is probably dependent in great part on the action of the soluble products of vegetable decomposition, aided by the elevated temperature. It, however, requires careful investigation; and a consideration of the causes which have induced it, and the extent to which it may have in former periods prevailed on the earth's surface, is of great geological importance, since the immense erosion of which geognosy affords us evidence, and which seems so difficult to explain if we conceive the rocks to have been as hard as we now find them in many regions, becomes more easily intelligible if we suppose the cohesion of the crystalline rocks to have been previously much weakened by decay.

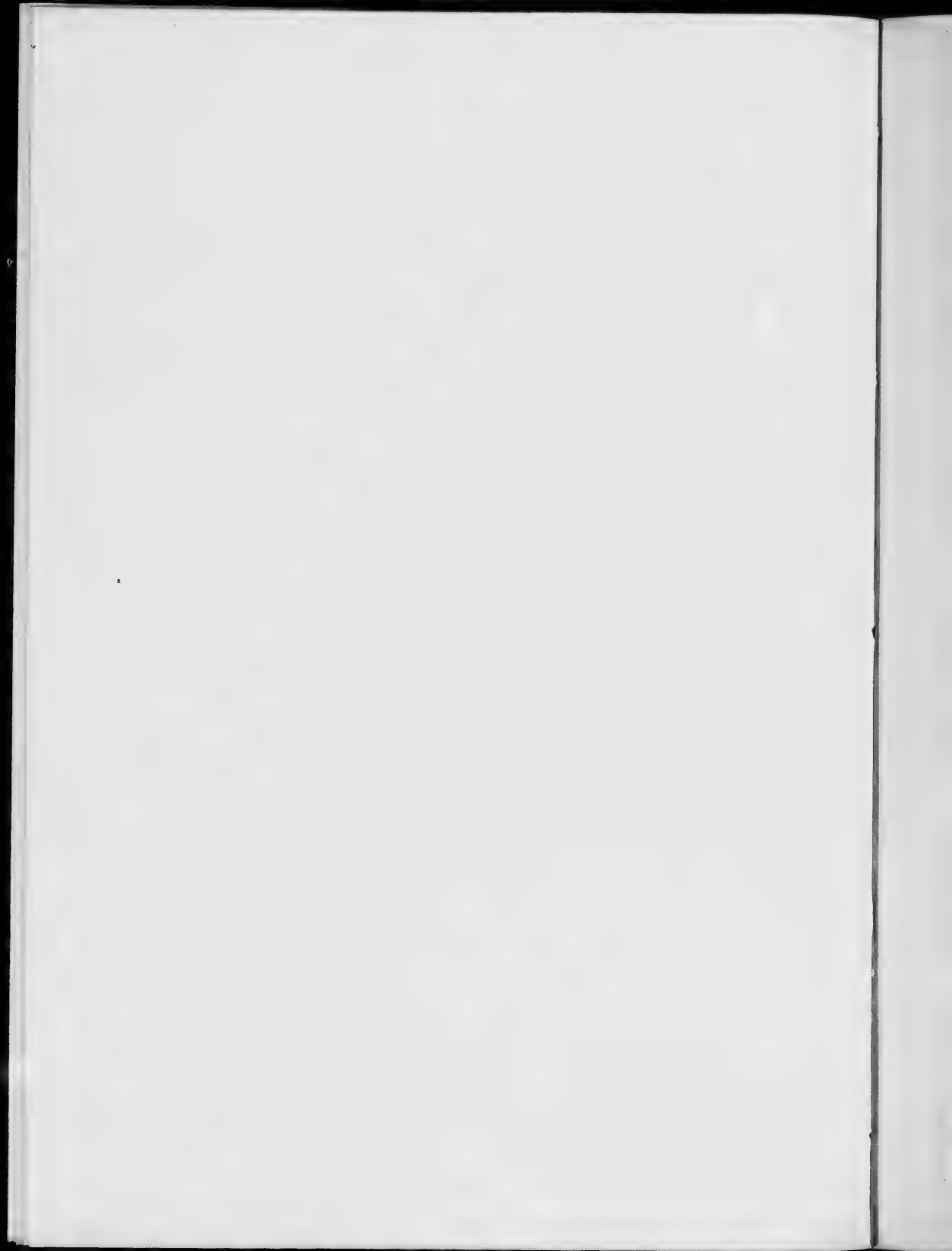
§ 27. The operation of the mechanical and chemical agencies which preside over the disintegration of pre-existing rocks naturally divides the insoluble products into two types, approaching in chemical composition, as we have shown, to granites, gneiss, and mica-schist, on the one hand,

and to diorites and dolerites on the other. These correspond to the two classes of igneous rocks designated by Bunsen as the trachytic and pyroxenic types.

§ 28. There is, however, a third source of silicated rocks, to which some allusion has already been made in speaking of the production of magnesian silicates by direct precipitation, as the result of chemical changes in solutions. In this way have been formed, besides these and related protoxide silicates, other silicates, including alumina. This base in certain conditions as yet but imperfectly understood, passes into solution in water, and has given rise to complex silicates, including protoxide bases. As I have elsewhere expressed it, not only steatite, pyroxene, hornblende, and serpentine, but chlorite and, in many cases, garnet and epidote, have had their origin in the crystallization and molecular re-arrangement of natural silicates, generated by chemical processes in aqueous solutions at the earth's surface. To these must be added other silicates, containing alkalis, chiefly potash, such as glauconite, and a hydrous silicate of alumina and potash which has the composition of pinite or agalmatolite and forms beds in the sedimentary rocks of different geological periods. Evidences abound of the solution of alumina, and of the generation, as chemical precipitates, of various aluminiferous silicates. These, like the similarly-formed protoxide silicates, are in most, if not all cases, highly basic, and moreover, from the mechanical conditions of their production and deposition, are found associated and even intermingled with the finely-divided basic sediments of mechanical origin. The aluminous silicates thus formed, though mineralogically important, are probably small in amount when compared with the great mass of argillaceous sediments.

§ 29. The chemical changes which are wrought in the silicated rocks during their mechanical disintegration are, as we have seen, chiefly the elimination of the alkalis, especially the soda, in a soluble form from its aluminous compounds, and the separation and accumulation of the oxide of iron. The decomposition of the silicates of lime and magnesia which takes place is, to a great extent, compensated for by the regeneration of similar compounds by the reaction already explained, but the mean composition of the argillaceous sediments of any geological epoch will depend not only upon the age of a formation, but upon the number of times which its materials have been broken up, and the length of the periods during which they have been exposed, in an unmetamorphosed condition, to the action of water, carbonic acid, and vegetation. If, however, we may assume that this action, other things being equal, has on the whole been most complete in the newest formations, it is evident that the chemical and mineralogical composition of different systems of rocks must vary with their antiquity, so that we may find in their comparative study a guide to their respective ages. Silicious deposits, and chemical precipitates, like the carbonates and silicates of lime and magnesia, may exist, with similar characters, in the geological formations of any age,* not only forming beds apart, but mingled with the less permeable silico-aluminous sediments of mechanical origin. Inasmuch as the chemical agencies giving rise to these compounds were then most active, they may be expected in greatest abundance in the rocks of the earlier periods. In the case of the more permeable and more highly silicious sediments already noticed, (§ 24,) whose principal elements are silica, alumina, and alkalis, the deposits of different ages will be marked chiefly by a progressive diminution in the amount of potash and in the disappearance of the soda which they contain. In the oldest or least

* *Geology of Canada, Report, 1866, page 230.*



lixivated rocks the proportion of alkali will be nearly or quite sufficient to form orthoclase or albite with the whole of the alumina present, but as the alkali diminishes, a portion of the alumina will crystallize, upon the metamorphism of the sediments, in the form of a potash-mica, such as muscovite or margarodite. While the oxygen-ratio between the alumina and the alkali in the feldspars just named is 3:1, it becomes 6:1 in margarodite and 12:1 in muscovite. The appearance of these micas in an aluminous rock denotes, then, a diminution in the amount of alkali, until in some strata the feldspar almost entirely disappears, and the rock becomes a quartzose mica-schist. In sediments still further deprived of alkali, metamorphism gives rise to schists filled with crystals of kyanite or of andalusite, simple silicates of alumina, into which alkalies do not enter, at least in noticeable quantities; but, in case the sediment still retains oxide of iron, staurolite and iron-garnet take their place. The matrix of all these minerals is generally a micaceous schist. The last term in this exhaustive process appears to be represented by the disthene and pyrophyllite rocks which occur in some regions of crystalline schists. In conformity with what has just been pointed out, it will be seen that these aluminous silicates destitute of alkalies do not occur in the oldest known sediments; in those of the Laurentian system, in which also mica is found in comparatively small quantities, nearly all the alumina present being in the form of orthoclase or albite.*

§ 30. By metamorphism in geology is understood the change of chemical and mechanical sedimentary deposits into crystalline stratified rocks. The conversion of these sediments into definite mineral species has been effected in two ways: First, by molecular changes—that is to say, by a crystalline arrangement of particles of definite compounds previously formed; and, secondly, by chemical reactions between the elements in heterogeneous sediments, giving rise to new compounds, which become crystalline in their turn. Pseudomorphism, which is the change of one mineral species into another by the introduction or the elimination of some element or elements, presupposes metamorphism, since only definite mineral species can be the subjects of this process. To confound metamorphism with pseudomorphism, as Bischof and others after him have done, is therefore an error. It may be further remarked that although certain pseudomorphic changes may take place in some mineral species existing in veins and near to exposed surfaces, the alteration of great masses of silicated rocks by such a process is as yet an unproved hypothesis.

§ 31. The cases of local metamorphism in proximity to intrusive rocks go far to show, in opposition to the views of certain geologists, that heat has been one of the necessary conditions of the chemical change. The source of this heat is generally admitted to be from below, but to the hypothesis of alteration by ascending heat Naumann has objected that the inferior strata in some cases escape change, and that, in descending, a certain plane limits the metamorphism, separating the altered strata above from the unaltered strata beneath, there being no apparent transition between the two. This, taken in connection with the well-known fact that in many cases the intrusion of igneous rocks causes no apparent change in the adjacent unaltered sediments, shows that heat and moisture are not the only conditions of metamorphism. I showed, by experiments in 1857, that, in addition to these conditions, certain

* For a discussion of this subject see my paper on The Chemical and Mineralogical Relations of Metamorphic Rocks, Dublin Quarterly Journal of Science, July, 1863; also Geology of Canada, 1863, page 561, and chap. XIX, of the same work.

chemical reagents might be necessary, and that water impregnated with alkaline carbonates and silicates would, at a temperature not above 100° centigrade, produce chemical reactions among the elements of many sedimentary rocks, dissolving silica and generating various insoluble silicates.* Subsequent experiments by Daubrée confirmed these results of mine, and both together showed the agency of heated alkaline waters to be sufficient to effect the metamorphism of sediments by the two modes already mentioned, namely, by molecular changes and by chemical reactions.

§ 32. Daubrée further showed, by his observations on the thermal alkaline spring at Plombières, that its waters, at a temperature of 70° centigrade, had in the course of centuries given rise to the formation of zeolites and other crystalline silicated minerals among the bricks and mortar of the old Roman baths. The influence of similar waters may account for many cases of local metamorphism, but is utterly inadequate to explain the complete and universal alteration of great areas of sedimentary rocks, embracing many hundreds or thousands of square miles. On the other hand, the study of the origin and distribution of mineral springs shows that alkaline waters, whose action in metamorphism I first pointed out, and whose efficient agency Daubrée has since so well shown, are confined to certain sedimentary deposits and to definite stratigraphical horizons, above and below which saline waters wholly different in character are found impregnating the strata. This fact offers a simple solution of the difficulty advanced by Naumann, and a complete explanation of the theory of metamorphism of deeply-buried strata by the agency of ascending heat, which is operative in producing chemical changes only in those strata in which soluble alkaline salts are present.

§ 33. We have said that the metamorphism of sediments includes both chemical and crystallogenic changes. The gradual transformation of amorphous precipitates under water into crystalline aggregates, so often observed in the laboratory, appears to depend upon partial solution and re-deposition of the material, which must not be entirely insoluble in the surrounding liquid. If the solvent power of this be reduced, the dissolved portions are deposited on certain particles rather than others. By a subsequent exaltation of the solvent power of the liquid, solution of a further portion takes place, and this, in its turn, is deposited around the nuclei already formed, which are thus augmented at the expense of the smaller particles, until these at length disappear, being gathered to the crystalline centers. Such a process, which has been studied by H. Deville, suffices, under the influence of the changing temperature of the seasons, to convert many fine precipitates into crystalline aggregates, by the aid of liquids of slight solvent powers. A similar agency may be supposed to have effected the crystallization of buried sediments, and changes in the solvent power of the permeating water might be due either to variations of temperature or of pressure. Simultaneously with this process one of chemical union of heterogeneous elements may go on, and in this way, for example, we may suppose the carbonates of lime and magnesia become united to form dolomite or magnesian limestone. (§ 20.)

§ 34. When the sedimentary strata have thus been rendered crystalline by metamorphism, their permeability to water and their alterability thereby become greatly diminished; and it is only when again broken down by mechanical agencies to the condition of soils and sediments that they once more become subject to the chemical changes which have

* T. S. Hunt, *American Journal of Science*, [2.] xxiii, 407; xxv, 287-437.

been described in § 23. While the crystalline stratified rocks are but slightly porous the unaltered strata hold large quantities of water in their pores. The mean of thirty-six determinations upon sandstones, shales, limestones, and dolomites from twenty-five different localities among the unaltered paleozoic sediments of Canada showed that 7.75 volumes of water were held in 100 volumes of the thoroughly-moistened rock. The proportion varied from less than 1.0 per cent. in the more compact limestones, to 10.0 and even 21.0 per cent. in the sandstones, an amount which is greatly exceeded in some more recent limestones.* A large proportion of the ocean's waters is thus imprisoned in the vast volume of unaltered sediments, and set free when these become metamorphosed, a process which is attended with a corresponding reduction of volume. In addition to this, moreover, the clays and other hydrated silicates lose a large part of their chemically-combined water during metamorphism, and become changed into crystalline compounds of increased density. This becomes obvious when we compare the specific gravity of such species as garnet, epidote, chloritoid, staurolite, andalusite and kyanite with that of the unaltered sediments in the midst of which they are generated. From this condensation, then, as well as from the mechanical contraction consequent upon the expulsion of water, the metamorphism of sediments is attended with a very considerable diminution of bulk, which is not without geological significance. It results from the experiments of Sorby (§ 14) that such chemical changes as are accompanied by condensation or diminution of volume are favored and accelerated by pressure, which may thus become a direct agent in promoting metamorphism as well as solution.

§ 35. The crystallization which takes place in sedimentary rocks not unfrequently effaces more or less completely the traces of their stratified and sedimentary origin, as is seen, for example, in many gneisses, which are scarcely distinguishable from granite. The study of such rocks, moreover, affords abundant proof that this alteration has been attended with such a softening that the material has been molded by pressure, forced into fissures or openings in less fusible or less heated strata, and thus taken the form of what is designated as eruptive rocks. The action of heat upon sedimentary rocks is not, however, confined to condensation, crystallization, and softening; strata in which carbonates, sulphates, chlorides, and carbonaceous substances are mingled with silicious and argillaceous matters, will, at a sufficiently-elevated temperature, in the presence of water, undergo such changes as must liberate carbonic acid, hydrochloric acid, and sulphuretted hydrogen, which are the common gaseous accompaniments of volcanic action. From these considerations we are led to a rational theory of volcanic and eruptive rocks, which we conceive to have their seat, not in an uncongealed portion of the once liquid globe, but in the more deeply-buried portions of that disintegrated crust whose origin has been explained in § 14.

§ 36. The history of this theory forms an interesting chapter in geology. As remarked by Humboldt, a notion that volcanic phenomena have their seat in the sedimentary formations, and are dependent on the combustion of organic substances, belongs to the infancy of geology. To this period belong the theories of Lémery and Breislak, (*Cosmos*, v. 443; Otte's translation.) Keferstein, in his *Naturgeschichte des Erdkörpers*, published in 1834, maintained that all crystalline non-stratified rocks, from granite to lava, are products of the transformation of sedimentary strata, in part very recent, and that there is no well-defined

* Geological Report of Canada, 1866, p. 283.—American Journal of Science, [2], xxxix, 183.

line to be drawn between neptunian and volcanic rocks, since they pass into each other. Volcanic phenomena, according to him, have their origin, not in an igneous fluid center, nor in an oxidizing metallic nucleus, (Davy, Daubeny,) but in known sedimentary formations, where they are the result of a peculiar kind of fermentation, which crystallizes and arranges in new forms the elements of the sedimentary strata, with an evolution of heat as a result of the chemical process, (*Naturgeschichte*, vol. i, p. 109; also *Bulletin de la Société Géologique de France*, [1], vol. vii, p. 197.) In commenting upon these views, (*American Journal of Science*, July, 1860,) I have remarked that, by ignoring the incandescent nucleus as a source of heat, Keferstein has excluded the true exciting cause of the chemical changes which take place in the buried sediments. The notion of a subterranean combustion or fermentation, as a source of heat, is to be rejected as irrational.

§ 37. A view identical with that of Keferstein, as to the seat of volcanic phenomena, was soon after put forth by Sir John Herschel, in a letter to Sir Charles Lyell, in 1836, (*Proceedings of the Geological Society of London*, ii, 548.) Starting from the suggestion of Scrope and Babbage, that the isothermal horizons in the earth's crust must rise as a consequence of the accumulation of sediments, he insisted that deeply-buried strata will thus become crystallized by heat, and may eventually, with their included water, be raised to the melting point, by which process gases would be generated, and earthquakes and volcanic eruptions follow. At the same time the mechanical disturbance of the equilibrium of pressure, consequent upon a transfer of sediments, while the yielding surface reposes on matters partly liquified, will explain the movements of elevation and subsidence of the earth's crust. Herschel was probably ignorant of the extent to which his views had been anticipated by Keferstein; and the suggestions of the one and the other seemed to have passed unnoticed by geologists until, in March, 1858, I reproduced them in a paper read before the Canadian Institute, (Toronto,) being at that time acquainted with Herschel's letter, but not having met with the writings of Keferstein. I there considered the reactions which would take place under the influence of a high temperature in sediments permeated with water, and containing, besides silicious and aluminous matters, carbonates, sulphates, chlorides, and carbonaceous substances. From these, it was shown, might be produced all the gaseous emanations of volcanic districts, while from aqueo-igneous fusion of the various admixtures might result the great variety of eruptive rocks. To quote the words of my paper just referred to: "We conceive that the earth's solid crust of anhydrous and primitive igneous rock is everywhere deeply concealed beneath its own ruins, which form a great mass of sedimentary strata, permeated by water. As heat from beneath invades these sediments, it produces in them that change which constitutes normal metamorphism. These rocks, at a sufficient depth, are necessarily in a state of igneo-aqueous fusion; and in the event of fracture in the overlying strata, may rise among them, taking the form of eruptive rocks. When the nature of the sediments is such as generate great amounts of elastic fluids by their fusion, earthquakes and volcanic eruptions may result, and these—other things being equal—will be most likely to occur under the more recent formations." (*Canadian Journal*, May, 1858, vol. iii, p. 207.)

§ 38. The same views are insisted upon in a paper "On some points in Chemical Geology." (*Quarterly Journal of the Geological Society*, London, November, 1859, vol. xv, page 594,) and have since been repeatedly put forward by me, with further explanations as to what I have designated

above, the ruins of the crust of anhydrous and primitive igneous rock. This, it is conceived, must, by contraction in cooling, have become porous and permeable, for a considerable depth, to the waters afterward precipitated upon its surface. In this way it was prepared alike for mechanical disintegration, and for the chemical action of the acids, which, as shown in § 16, must have been present in the air and the waters of the time. It is, moreover, not improbable that a yet unsolidified sheet of molten matter may then have existed beneath the earth's crust, and may have intervened in the volcanic phenomena of that early period, contributing, by its extravasation, to swell the vast amount of mineral matter then brought within aqueous and atmospheric influences. The earth, air, and water thus made to react upon each other, constitute the first matter from which, by mechanical and chemical transformations, the whole mineral world known to us has been produced.

§ 39. It is the lower portions of this great disintegrated and water-impregnated mass which form, according to the present hypothesis, the semi-liquid layer supposed to intervene between the outer solid crust and the inner solid and anhydrous nucleus. In order to obtain a correct notion of the condition of this mass, both in earlier and later times, two points must be especially considered, the relation of temperature to depth, and that of solubility to pressure. It being conceded that the increase of temperature in descending in the earth's crust is due to the transmission and escape of heat from the interior, Mr. Hopkins showed mathematically that there exists a constant proportion between the effect of internal heat at the surface and the rate at which the temperature increases in descending. Thus, at the present time, while the mean temperature at the earth's surface is augmented only about one-twentieth of a degree Fahrenheit, by the escape of heat from below, the increase is found to be equal to about one degree for each sixty feet in depth. If, however, we go back to a period in the history of our globe when the heat passing upwards through its crust was sufficient to raise the superficial temperature twenty times as much as at present, that is to say, one degree of Fahrenheit, the augmentation of heat in descending would be twenty times as great as now, or one degree for each three feet in depth, (*Geological Journal*, viii, 59.) The conclusion is inevitable that a condition of things must have existed during long periods in the history of the cooling globe when the accumulation of comparatively thin layers of sediment would have been sufficient to give rise to all the phenomena of metamorphism, vulcanicity, and movements of the crust, whose origin Herschel has so well explained.

§ 40. Coming, in the next place, to consider the influence of pressure upon the buried materials derived from the mechanical and chemical disintegration of the primitive crust, we find that by the presence of heated water throughout them, they are placed under conditions very unlike those of the original cooling mass. While pressure raises the fusing point of such bodies as expand in passing into the liquid state, it depresses that point for those which, like ice, contract in becoming liquid. The same principle extends to that liquefaction which constitutes solution; where, as is with few exceptions the case, the process is attended with condensation or diminution of volume, pressure will, as shown by the experiments of Sorby, augment the solvent power of the liquid. Under the influence of the elevated temperature, and the great pressure which prevail at considerable depths, sediments should, therefore, by the effect of the water which they contain, acquire a certain degree of liquidity, rendering not improbable the suggestion of Scheerer, that the presence of five or ten per cent. of water may suffice, at temperatures approaching red-

ness, to give to a granitic mass a liquidity partaking at once of the character of an igneous and an aqueous fusion. The studies by Mr. Sorby of the cavities in crystals have led him to conclude that the constituents of granitic and trachytic rocks have crystallized in the presence of liquid water, under great pressure, at temperatures not above redness, and consequently very far below that required for simple igneous fusion. The intervention of water in giving liquidity to lavas, has, in fact, long been taught by Scrope, and notwithstanding the opposition of plutonists like Durocher, Fournet, and Rivière, is now very generally admitted. In this connection, the reader is referred to the *Geological Magazine* for February, 1868, page 57, where the history of this question is discussed.

§ 41. It may here be remarked that if we regard the liquefaction of heated rocks under great pressure, and in presence of water, as a process of solution rather than of fusion, it would follow that diminution of pressure, as supposed by Mr. Scrope, would cause not liquefaction, but the reverse. The mechanical pressure of great accumulations of sediment is to be regarded as co-operating with heat to augment the solvent action of the water, and as being thus one of the efficient causes of the liquefaction of deeply-buried sedimentary rocks.

§ 42. That water intervenes not only in the phenomena of volcanic eruptions, but in the crystallization of the minerals of eruptive rocks, which have been formed at temperatures far below that of igneous fusion, is a fact not easily reconciled with either the first or the second hypothesis of volcanic action, but is in perfect accordance with the one here maintained, which is also strongly supported by the study of the chemical composition of igneous rocks. These are generally referred to two great divisions, corresponding to what have been designated the trachytic and pyroxenic types, (§ 27,) and to account for their origin, a separation of a liquid igneous mass beneath the earth's crust into two layers of acid and basic silicates was imagined by Phillips, Durocher, and Bunsen. The latter, as is well known, has calculated the normal composition of these supposed trachytic and pyroxenic magmas, and conceives that from them, either separately or by admixture, the various eruptive rocks are derived; so that the amounts of alumina, lime, magnesia, and alkalis sustain a constant relation to the silica in the rock. If, however, we examine the analyses of the eruptive rocks in Hungary and Armenia, made by Streng, and put forward in support of this view, there will be found such discrepancies between the actual and the calculated results as to throw grave doubts on Bunsen's hypothesis.

§ 43. Two things become apparent from a study of the chemical nature of eruptive rocks: first, that their composition presents such variations as are irreconcilable with the simple origin generally assigned to them; and second, that it is similar to that of sedimentary rocks whose history and origin it is, in most cases, not difficult to trace. We have already pointed out (§ 27) how the natural operation of mechanical and chemical agencies tends to produce among sediments a separation into two classes, corresponding to the two great divisions above noticed. From the mode of their accumulation, however, great variations must exist in the composition of the sediments, corresponding to many of the varieties presented by eruptive rocks. The careful study of stratified rocks of aqueous origin discloses, in addition to these, the existence or deposits of basic silicates of peculiar types. Some of these are in great part magnesian; others consist of compounds like anorthite and labradorite, highly aluminous basic silicates, into which lime and soda enter, to the almost complete exclusion of magnesia and other bases; while in the masses of pinité or agalmatolite rock we have a similar aluminous

silicate, in which lime and magnesia are wanting, and potash is the predominant alkali, (§ 28.) In such sediments as these just enumerated we find the representatives of eruptive rocks like peridotite, phonolite, leucitophyre, and similar rocks, which are so many exceptions in the basic group of Buksen. As, however, they are represented in the sediments of the earth's crust, their appearance as exotic rocks, consequent upon a softening and extravasation of the more easily liquefiable strata of deeply-buried formations, is readily and simply explained.

§ 44. In this connection a few words may be said about the popular notion which makes granite the substratum of all stratified formations, and even identifies it with the supposed primitive crust of the globe. That this crust is everywhere concealed beneath its own ruins, and, moreover, that its composition must have been very different from granite, we have endeavored to explain, (§ 16.) The Laurentian, the oldest known system of rocks, includes in its vast volume great interstratified masses of gneiss, often closely resembling granite, and it is extremely probable that these, softened and extravasated, may form the eruptive granites which break through more recent systems of strata. These granitic gneisses are, however, clearly stratified, and hold, moreover, intercalated beds of quartzite and of limestone, often of great volume, and including the remains of an animal organism—the *Eozoon Canadense*. The predominance of feldspar, which gives the granitic character to the aluminous rocks of early periods, has already been explained in § 29 as resulting from the great abundance of combined alkalis in these ancient rocks. The presence of quartz, an essential element alike in gneiss and granite, would suffice to show that granite is in all cases a secondary or derived rock, formed under aqueous influences—even had Sorby not shown that the minute crystal-cavities in the quartz of granitic rocks contain liquid water which must have been introduced at the time of crystallization. Quartz has not only never been met with as a result of igneous fusion, but it is clearly shown by the experiments of Rose that a heat even much less than that required for the fusion of quartz destroys it, changing it into a new substance, which differs both in chemical and physical properties from quartz. We have pointed out in § 16 the chemical process by which it may be supposed that silica was set free from the primitive silicated mass, under conditions which would permit its conversion into quartz.

§ 45. The rocks mentioned in preceding sections are, as regards their geognostical relations, divided into stratified or indigenous and erupted or exotic rocks, the latter being looked upon as the results of the softening and displacement of the former. Besides these, it is necessary to distinguish a third kind of rock-masses, which, like the latter, occupy fissures in previously-formed rocks, but are unlike them in origin, and have been deposited from aqueous solutions. The most familiar form of these is met with in the vein-stones of quartz, calcite, barytine, and fluor, which are often the gangue of metallic ores. A careful study of the various kinds of veins and their relations leads us, however, to admit that almost all the mineral species which occur in the preceding classes of rocks may exist in vein-stones, which, from the mode of their production, we have designated endogenous rocks. Calcareous veins in the Laurentian rocks may contain all the mineral species of indigenous limestones, and quartzo-feldspathic veins are made up of aggregates which are familiarly designated as granites. To these, in fact, belong all those so-called granitic veins which are marked by containing fine crystallizations or rare mineral species. When, as is often the case, these marks

are wanting it is sometimes difficult to distinguish in hand-specimens between indigenous, exotic, and endogenous granites.

§ 46. The deposition of these mineral species from solution has doubtless taken place under considerable degrees of heat and pressure, which could only exist at great depths in the earth's crust. Waters charged with mineral elements by percolation through deeply-seated strata rise through fissures in these and deposit along the channels their dissolved matters, a process not so much the result of cooling as of that decrease of solvent power which must follow the diminution of pressure in accordance with Sorby's conclusions.*

§ 47. As pointed out in § 17, the first precipitates from the water of the primeval sea must have contained oxidized compounds of most of the heavy metals. These early deposits, by mechanical division or by solution, became subsequently diffused, and entered into the composition of later sedimentary strata. Removed from these by watery solution, the metallic compounds have been, in different ages, brought to the surface to be deposited in some cases as oxides or carbonates, or reduced by the action of organic matters to the state of sulphurets or native metals, and mingled with the contemporaneous sediments in beds or in disseminated grains. During the subsequent alteration of the strata, these metallic matters, being taken into solution, have been re-deposited in fissures in the metalliferous strata, forming veins, or, ascending to higher beds, have given rise to metal-bearing veins in strata not themselves metalliferous. The metals of the sedimentary rocks are now, however, for the greater part, in the form of insoluble sulphurets, so that we have only traces of them in a few mineral springs, which serve to give a faint notion of the agencies at one time at work in the sediments and waters of the earth's crust. Like the iron, (§ 19) these metals have been in great part withdrawn from the terrestrial circulation. The frequent occurrence of these metals in waters which are alkaline from the presence of carbonate of soda, is significant, when taken in connection with the metalliferous character of certain dolomites, which probably owe their origin to the action of similar alkaline springs upon basins of sea-water, (§ 20.) The intervention of intense heat and fusion or sublimation to explain the origin of metallic ores is uncalled for. The solvent powers of water and of various saline, alkaline, and sulphuretted solutions at high temperatures, in connection with the notions above enunciated, will suffice to form the basis of a rational theory of metallic deposits.†

§ 48. The consideration of the nature and origin of endogenous rocks has led to a digression to discuss the theory of metalliferous veins, which the plan of this essay did not permit us to treat before. We now resume the line of inquiry followed from § 36 to § 43, and proceed to consider the phenomena of volcanoes and earthquakes in accordance with the notions already put forward.

Violent movements of the earth's crust are confined to certain regions of the globe, which are at the same time characterized by volcanic

* Of this a remarkable example was afforded in 1866 at Goderich, in Ontario, where, at a depth of 1,000 feet, a bed of rock-salt was met, from which for a time a saturated or rather supersaturated brine was obtained. As an evidence of this, I saw a cube of pure salt, one-fourth of an inch in diameter, which had formed upon and around a projecting point of an iron valve in the pump, above the surface of the ground. The liquid beneath a pressure of 1,000 feet of brine, equal to about 1,200 feet of water, or 36 atmospheres, having taken up more salt than it could hold at the ordinary pressure, deposited a portion of it as it reached the surface, and actually obstructed thereby the action of the pump. After a few months of pumping, however, the well ceased to afford a fully saturated brine.

† American Journal of Science, [2.] xxxi, 405, and xl, 213.

activity; from which it is reasonably inferred that the phenomena of earthquakes and volcanoes have a common origin. The discharge through openings in the earth's crust, of ignited stony matter, generally in a fused condition, and the disengagement of various gases and vapors, accompanied by movements of elevation or subsidence of considerable areas of the earth's surface, sometimes rapid and paroxysmal, and attended with great vibratory movements, are evidences of a yielding crust of solid rock resting upon an igneous and fluid mass below. To the same conditions are also to be ascribed the slow movements of portions of the earth's surface, shown in the rise and fall of continents in regions remote from centers of volcanic activity. The unequal tension of the yielding crust and the sudden giving way of the overstrained portions are probably the immediate cause of earthquake phenomena; the seat of these, according to the deductions of Mallet, is to be found at depths of from seven to thirty miles from the surface.

§ 49. A brief description of the phenomena of volcanoes will here be necessary. Volcanoes are openings in the earth's crust through which are discharged solid, liquid, and gaseous matters, generally in an intensely heated condition. Sometimes the ejected material is solid, and consists of broken, comminuted rock, or the so-called volcanic ashes. Oftener, however, it is discharged in a more or less completely fused condition, constituting lava, which is sometimes fluid and glassy, but more frequently pasty and viscid, so that it flows slowly and with difficulty. The ejected materials, whether liquid or solid, build up volcanic cones by successive layers—a fact which has been established by modern observers in opposition to the notion come down from antiquity, that volcanic hills are produced by an uprising or tumefaction of previously horizontal layers of rock by the action of a force from beneath. First among the gaseous products of volcanoes is watery vapor; water appears not only to be involved in all volcanic eruptions, but to be intimately combined with the lavas, to which, as Scrope has shown, it helps to give liquidity. The water at this high temperature is retained in combination under great pressure, but as this pressure is removed passes into the state of vapor, a process which explains the swelling up of lavas and their rise in the craters of the volcanoes. Besides watery vapor, carbonic and hydrochloric acid gases, and hydrogen, both free and combined with sulphur and with carbon, are products of volcanoes. The combustion of the inflammable gases in contact with air sometimes give rise to true burning mountains—a name which does not properly belong to such as give out only acid gases, steam, and incandescent rocky matters, which are incombustible.

§ 50. The escape of elastic fluids from lavas gives to them a cellular structure, but when slowly cooled under pressure, as seen in the dykes traversing the flanks of volcanoes, the stony materials assume a more solid and crystalline condition, and resemble the older eruptive rocks found in regions not now volcanic. These include granites, trachytes, dolerites, basalts, &c., and are masses of rock which, though extravasated after the manner of lavas, became consolidated in the midst of surrounding rocks, and consequently under considerable pressure, (§ 37.) Their presence marks either the lower portions of volcanoes whose cones have been removed by denudation, or outbursts of liquefied rock which never reached the surface. The escape of such matters, and the formation of volcanic vents, are but accidents in the history of the igneous action going on beneath the earth's surface. We shall, therefore, regard the extravasation of igneous matter, whether as lava or ashes at the surface, or as plutonic rock in the midst of strata, as, in its

wider sense, a manifestation of vulcanicity, and for the elucidation of our subject consider both those regions characterized by great outbursts of plutonic rock in former geologic periods and those now the seats of volcanic activity, which, in these cases, can generally be traced back some distance into the tertiary epoch. To begin with the latter, the first and most important is the great continental region which may be described as including the Mediterranean and Aralo-Caspian basins, extending from the Iberian Peninsula eastward to the Thian-Chan Mountains of Central Asia. In this great belt, extending over about ninety degrees of longitude, are included all the historic volcanoes of the ancient world, to which we must add the extinct volcanoes of Murcia, Catalonia, Auvergne, the Vivarais, the Eifel, Hungary, &c., some of which have probably been active during the human period.*

Besides the great region just indicated, must be mentioned that of our own Pacific slope, from Fuegia to Alaska, from whence, along the eastern shore of Asia, a line of volcanic activity extends to the terrible burning mountains of the Indian archipelago. Volcanic islands are widely scattered over the Pacific basin, and volcanoes burn amid the thick-ribbed ice of the Antarctic continent. The Atlantic area is in like manner marked by volcanic islands from Jan Mayen and Iceland to the Canaries, the Azores, and the Caribbean Islands, and southward to Ascension, St. Helena, and Tristan d'Acunha.

§ 51. The continents, with the exception of the two areas already defined, present no evidences of modern volcanic action, and the regions of ancient volcanic activity, as shown by the presence of great outbursts of eruptive rocks, are not less limited and circumscribed. In northern Europe the chain of the Urals, an area in central Germany, and one in the British Islands are apparent, and in North America there appear to have been but two volcanic regions in the paleozoic period—one in the basin of Lake Superior, and another, which may be described as occurring along either side of the Appalachian chain to the northeast, including the valleys of the lower St. Lawrence, Lake Champlain, the Hudson and Connecticut Rivers, and extending still further southward. The study of the various eruptive rocks of this region shows that volcanic activity in different parts of it was prolonged from the beginning of the paleozoic period till after its close.

§ 52. The theory of Keferstein and Herschel, explained in § 37, shows in what manner volcanic phenomena may be directly dependent on the accumulation of sedimentary strata. It has already been shown that both temperature and pressure combine to produce in the lower portions

* It is a most significant fact that this region is nearly co-extensive with that occupied for ages by the great civilizing races of the world. From the plateau of Central Asia, throughout their westward migration to the pillars of Hercules, the Indo-European nations were familiar with the volcano and the earthquake; and that the Semitic race were not strangers to the same phenomena, the whole poetic imagery of the Hebrew Scriptures bears ample evidence. In the language of their writers, the mountains are molten, they quake and fall down at the presence of the Deity, when the melting fire burneth. The fury of His wrath is poured forth like fire; He toucheth the hills and they smoke; while fire and sulphur come down to destroy the doomed cities of the plain, whose foundation is a molten flood. Not less does the poetry and the mythology of Greece and Rome bear the impress of the nether realm of fire in which the volcano and the earthquake have their seat, and their influence is conspicuous throughout the imaginative literature and the religious systems of the Indo-European nations, whose contact with these terrible manifestations of unseen forces beyond their foresight or control could not fail to act strongly on their moral and intellectual development, which would have doubtless presented very different phases had the early home of these races been the Australian or the eastern side of the American continent, where volcanoes are unknown and the earthquake is scarcely felt. (From a lecture before the Amer. Geographical Society, April, 1869.)

of the sedimentary material a condition of igneo-aqueous fusion. It would be foreign to our plan to discuss in this place the agencies which, from early geologic periods, have been effecting the transfer of sediments, alternately wasting and building-up continents. One, however, requires notice in this connection, namely, the contraction of sediments consequent upon chemical changes, as already explained in § 34, which must result in subsidence. Such an effect may also result from the extravasation of great volumes of liquefied rock, and in either case the depressed portion of the surface becomes a basin, in which sediments may subsequently accumulate, and by their weight upon the yielding stratum beneath continue the process of subsidence. While the lower and more fusible strata becomes softened, the great mass of the more silicious rocks, losing their porosity, become cemented into a comparatively rigid mass, and finally, as a result of the earth's contraction, or to counter-balance the depression of some other region, are uplifted as a hardened and corrugated continental mass, from whose irregular erosion results a mountainous region.*

§ 53. Those strata which, from their composition, yield, under the conditions just described, the most liquid products, are, it is conceived, the source of all plutonic and volcanic rocks. Accompanied by water, and by difficulty coereble gases, they are either forced among the fissures which form in the overlying strata, or find their way to the surface. The variations in the composition of lavas and their accompanying gases in different regions, and even from the same vent at different times, are strong confirmations of the truth of this view. As explained in § 39, the semi-liquid layer of water-impregnated material constitutes a plastic bed, upon which the stratified sediments repose. These, by their irregular distribution over different portions of the earth, determined, after a lapse of time, in the regions of their greatest accumulation, volcanic and plutonic phenomena. It now remains to show the observed relation of these phenomena, both in the earlier and later times, to great accumulations of sediment.

§ 54. If we look at the North American continent, we find along its northeastern portion evidences of great subsidence and an accumulation of not less than 40,000 feet of sediment along the line of the Appalachians from the Gulf of St. Lawrence southward, during the paleozoic period, and chiefly, it would appear, during its earlier and later portions. This region is precisely that characterized by considerable eruptions of plutonic rocks during this period, and for some time after its close. To the westward of the Appalachians, the deposits of paleozoic sediments were much thinner, and in the Mississippi valley are probably less than 4,000 feet in thickness. Conformably with this, there are no traces of plutonic or volcanic outbursts from the northeast region just mentioned throughout this vast paleozoic basin, with the exception of the region of Lake Superior, where we find the early portion of the paleozoic age marked by a great accumulation of sediments, comparable to that occurring at the same time in the region of New England, and followed or accompanied by similar plutonic phenomena. Across the plains of northern Russia and Scandinavia, as in the Mississippi valley, the paleozoic period was represented by not more than 2,000 feet of sediments, which still lie undisturbed, while in the British Islands 50,000 feet of paleozoic strata, contorted and accompanied by igneous rocks,

* For a discussion of this subject and the theory of mountains, including the views of Professor James Hall, see the author on *American Geology*, *American Journal of Science*, [2] xxi, 406.

attest the connection between great accumulation and plutonic phenomena.

§ 55. Coming now to modern volcanoes, we find them in their greatest activity in oceanic regions, where subsidence and accumulation are still going on. Of the two continental regions already pointed out, that along the Mediterranean basin is marked by an accumulation of mesozoic and tertiary sediments, 20,000 feet or more in thickness. It is evident that the great mountain zone, which includes the Pyrenees, the Alps, the Caucasus and the Himalayah, was, during the later secondary and tertiary periods, a basin in which vast accumulations of sediments were taking place, as in the Appalachian belt during the paleozoic times. Turning now to the other continental region, the American Pacific slope, similar evidences of great accumulations during the same periods are found throughout its whole extent, showing that the great Pacific mountain belt of North and South America, with its attendant volcanoes, is, in the main, the geological equivalent or counterpart of the great east and west belt of the eastern world.

It is to be remarked that the volcanic vents are seldom immediately along the lines of greatest accumulation, but appear around and at certain distances therefrom. The question of the duration of volcanic activity in a given region is one of great interest, which cannot, for want of time, be considered here. It appears probable that the great manifestations of volcanic force belong to the period of depression of the area of sedimentation, if we may judge from the energy and copiousness of the eruptions of island volcanoes, although the activity is still prolonged after the period of elevation.

As regards the geological importance of volcanic and earthquake phenomena, their significance is but local and accidental. Volcanoes and earthquakes are and always have been confined to limited areas of the earth's surface, and the products of volcanic action make up but a small portion of the solid crust of the globe. Great mountains and mountain chains are not volcanic either in their nature or their origin, though sometimes crowned by volcanic cones; nor are earthquakes and volcanoes to be looked upon as anything more than incidental attendants upon the great agencies which are slowly but constantly raising and depressing continents.

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